SimBRS WD 43

Fleet Maintenance Simulation for Unmanned Ground Vehicles

Zissimos P. Mourelatos
Mechanical Engineering Department
Oakland University

Matthew P. Castanier, David A. Lamb
US Army TARDEC

SimBRS Program Review Meeting | 26-28 July 2011 | Starkville, MS

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **26 JUL 2011**	2. REPORT TYPE **Briefing Charts**	3. DATES COVERED **26-07-2011 to 26-07-2011**

4. TITLE AND SUBTITLE **FLEET MAINTENANCE SIMULATION FOR UNMANNED GROUND VEHICLES**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Matt Castanier; David Lamb; Zissimos Mourelatos**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Oakland University,Mechanical Engineering Department,Rochester,MI,48309**	8. PERFORMING ORGANIZATION REPORT NUMBER **; #22120**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC, 6501 E.11 Mile Rd, Warren, MI, 48397-5000**	10. SPONSOR/MONITOR’S ACRONYM(S) **TARDEC** 11. SPONSOR/MONITOR’S REPORT NUMBER(S) **#22120**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
SimBRS Program Review Meeting 26-28 July 2011 Starkville, MS

14. ABSTRACT
NA

15. SUBJECT TERMS

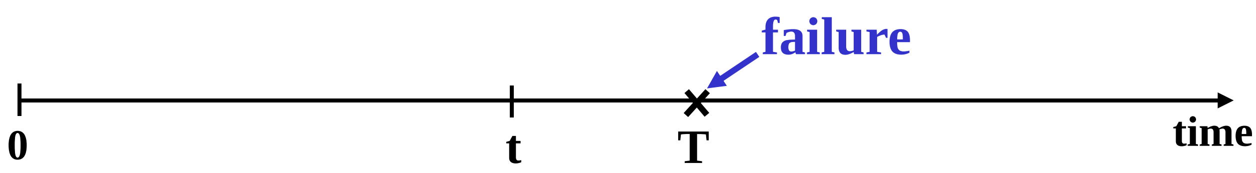
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**40**	

Overview

- What is reliability ?
- Basics of reliability methods for repairable and non-repairable systems
- Estimation of PDF of Time Between Failures (TBF) using limited, censored data
- System reliability and reliability allocation
- Fleet Maintenance Simulation (FMS) Tool
- Unmanned ground vehicle (UGV) system example

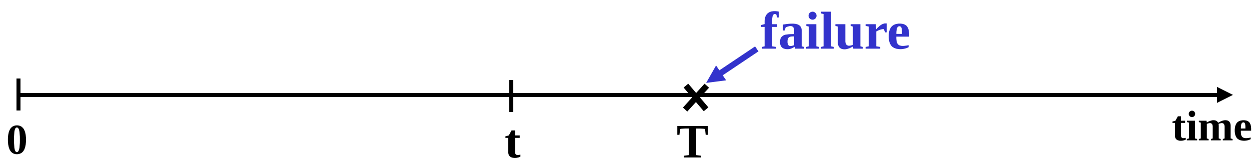
What is Reliability?

Reliability at time t is the probability that the system has not failed before time t.



$$\boxed{R(t) = P(T > t) = 1 - P(T \leq t)}$$

Reliability of Non-Repairable Systems



$$R(t) = P(T > t) = 1 - P(T \le t) \Rightarrow \boxed{R(t) = 1 - F(t)} \qquad \textbf{(1)}$$

Failure Rate

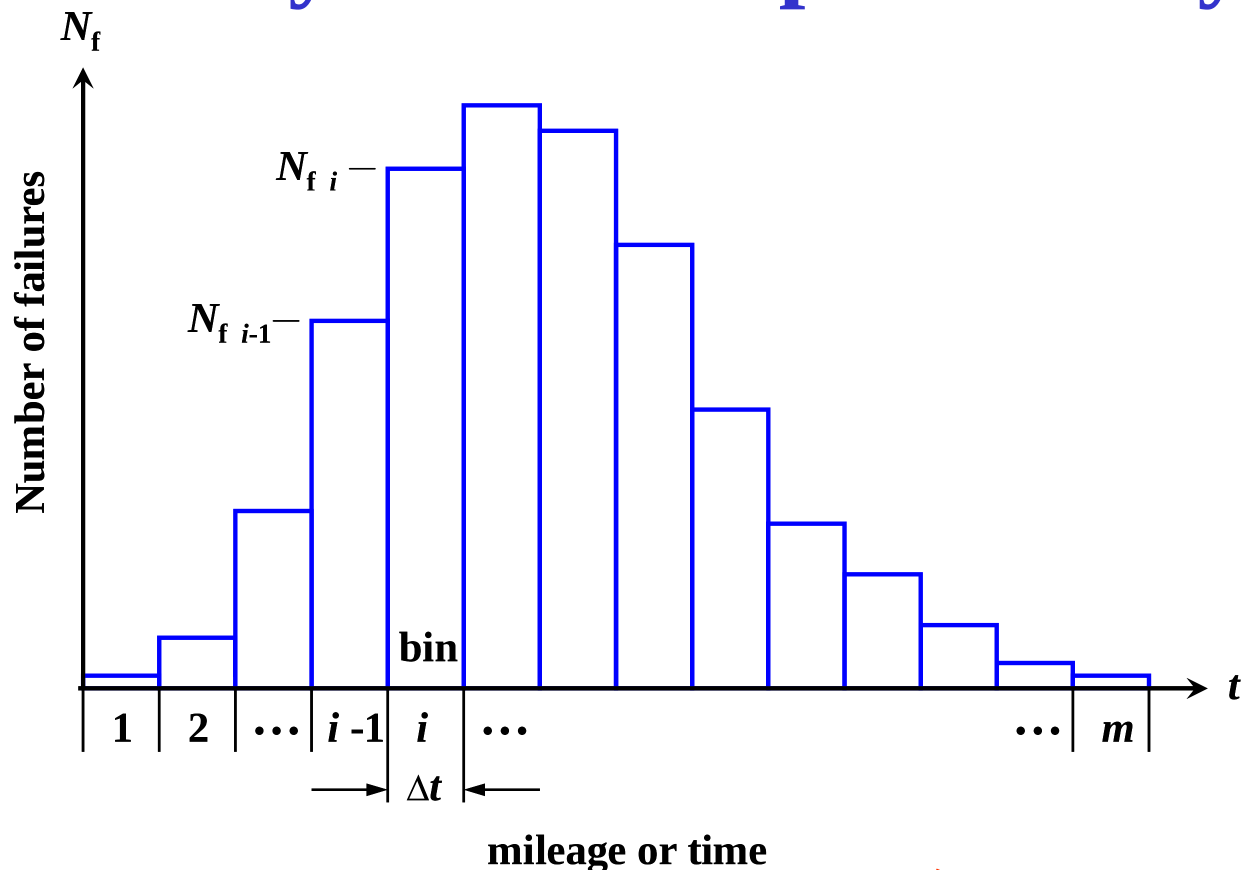
$$\lambda(t) = \frac{P(t < T \le t + dt / T > t)}{dt} = \frac{P(t < T \le t + dt)}{dt * P(T > t)} =$$

$$= \frac{F(t + dt) - F(t)}{dt * R(t)} \Rightarrow \boxed{\lambda(t) = \frac{f(t)}{R(t)}} \qquad \textbf{(2)}$$

From (1) and (2) we get :

$$\boxed{R(t) = \exp[-\int_0^t \lambda dt]}$$

Reliability of Non-Repairable Systems



$$N_f = \sum_{i=1}^{m} N_{f_i}$$

$$\lambda_i = \frac{f_i}{1-F_i} = \frac{f_i}{1-\sum_{j=1}^{i-1}\frac{N_{f_j}}{N_f}} = \frac{N_{f_i}}{\left(N_f - \sum_{j=1}^{i-1} N_{f_j}\right)\Delta t}$$

$$H_i = \sum_{j=1}^{i} \lambda_j \Delta t$$

$$\boxed{R_i = e^{-H_i}}$$

Reliability Calculation

All we need for calculating the reliability of a system (non-repairable or repairable) is the system PDF of time to failure (TTF)

We use :

- **Data to estimate the PDF of TTF for each component**
- **Monte Carlo simulation to estimate the PDF of TTF for the system**

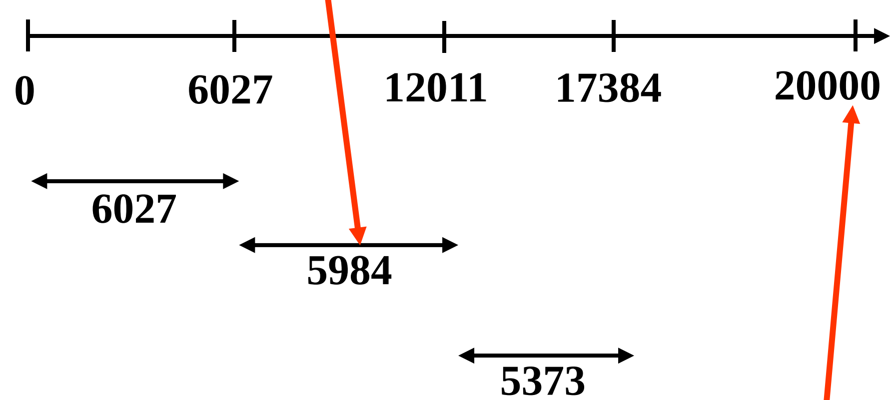
Estimation of the PDF of the TTF (TBF) using Limited, Censored Data

Censored MLE Approach

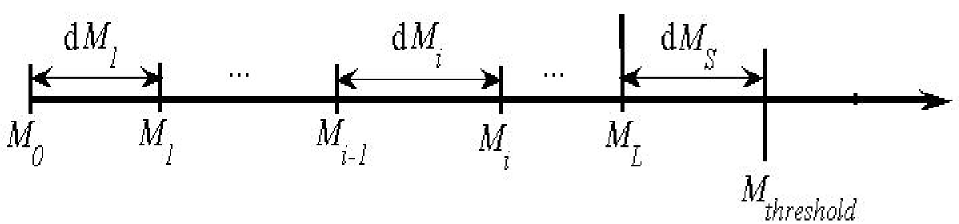
Limited Data / Notation

Original data Vehicle#	Original data mileage	Updated data Vehicle#	Updated data mileage
10	741	1	10247
4	5273	2	9044
7	6027	2	8977
5	7398	3	13984
6	7495	3	4064
2	9044	4	5273
1	10247	4	9747
8	12008	5	7398
7	12011	5	7611
9	12014	6	7495
10	12074	6	7516
3	13984	7	6027
5	15009	7	5984
6	15011	7	5373
4	15020	8	12008
7	17384	9	12014
2	18021	10	741
3	18048	10	11333

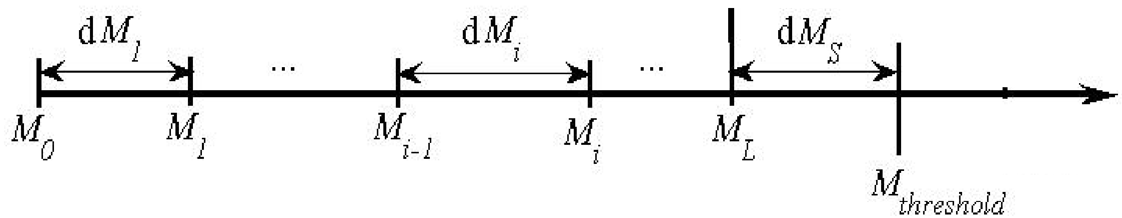
Time Between Failures (TBF)



Censoring Mileage

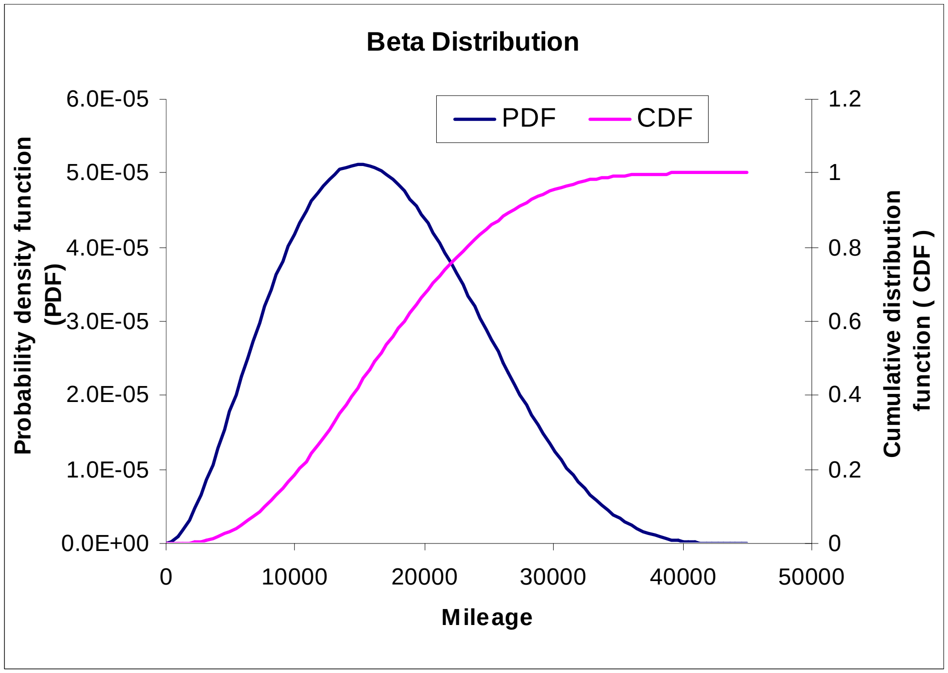


Observation / Assumption



$$\boxed{\mathrm{d}M_i = X_i \sim \beta(A, B, p, q), \quad (A \le X_i \le B, \text{ and } p > 0, q > 0)}$$

$$\boxed{f(x, A, B, p, q) = \beta(p,q)^{-1} (x - A)^{p-1} (B - x)^{q-1} / (B - A)^{p+q-1}, \quad (A \le x \le B, \textit{ and } p > 0, q > 0)}$$



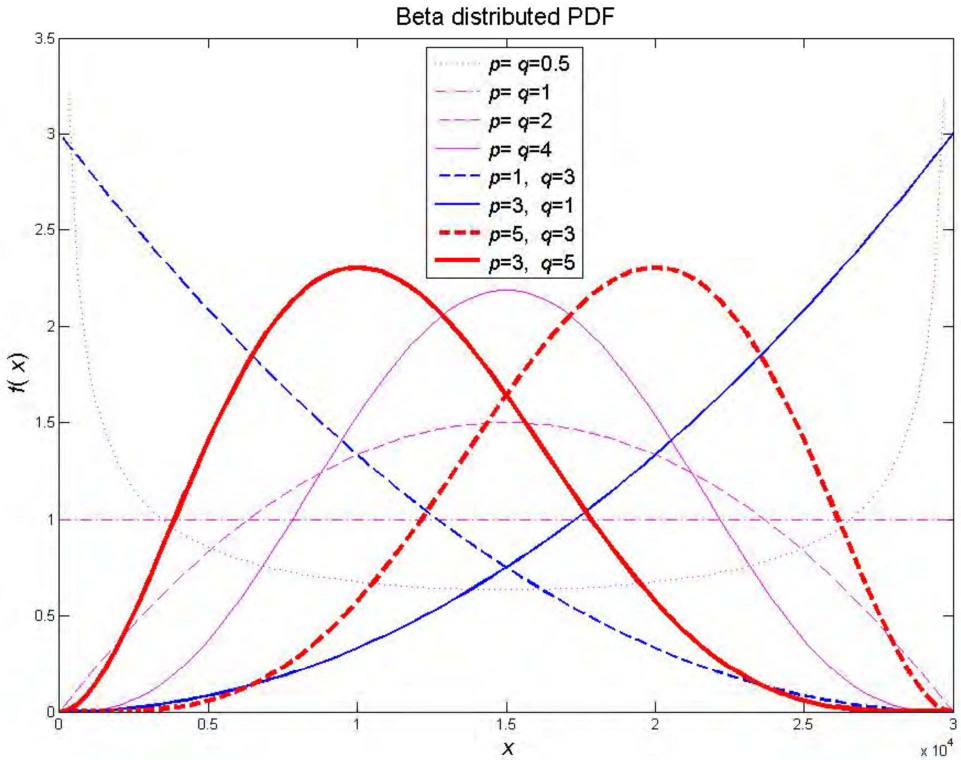
A = 0

B = 45,000 miles

p = 3, q = 5

Observation / Assumption

- **Beta distribution family is used to model TBF.**



A=0, B = 30000

$$f\left(x,A,B,p,q\right)=\beta\left(p,q\right)^{-1}\left(x-A\right)^{p-1}\left(B-x\right)^{q-1}/\left(B-A\right)^{p+q-1}, \quad \left(A\le x\le B, \text{ and } p>0,\, q>0\right)$$

MLE Approach

Determines parameters (*A, B, p, q*) of "most likely" Beta distribution using available data.

Censored MLE

# of recorded failures

# of survivals

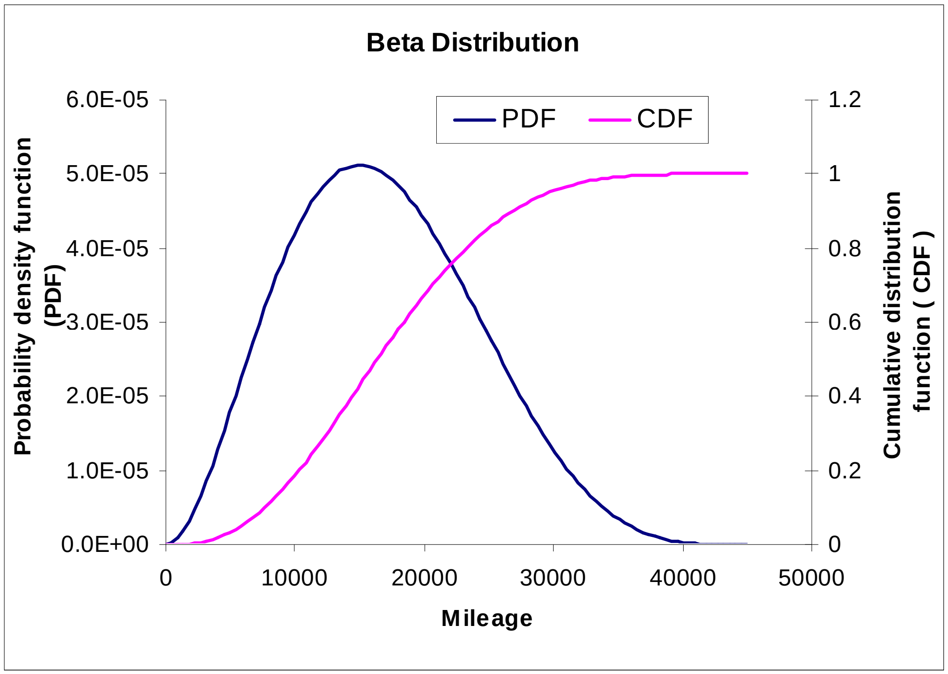
$$\underset{A,B,p,q}{Max} \prod_{i=1}^{N_F} f\left(x_i, A, B, p, q\right) \prod_{j=1}^{N_s} \left[1 - F\left(x_j, A, B, p, q\right)\right]$$

Beta PDF

Beta CDF

If Only MTBF is Available

$$f(x,A,B,p,q)=\beta(p,q)^{-1}(x-A)^{p-1}(B-x)^{q-1}/(B-A)^{p+q-1}, \quad (A\le x\le B,\ and\ \ p>0,\ q>0)$$



$$\mu = MTBF$$

Assume constant COV

Then for:

$$\bar{\mu} = \frac{\mu - A}{B - A} \quad \textbf{and} \quad \bar{\sigma} = \frac{\sigma}{B - A}$$

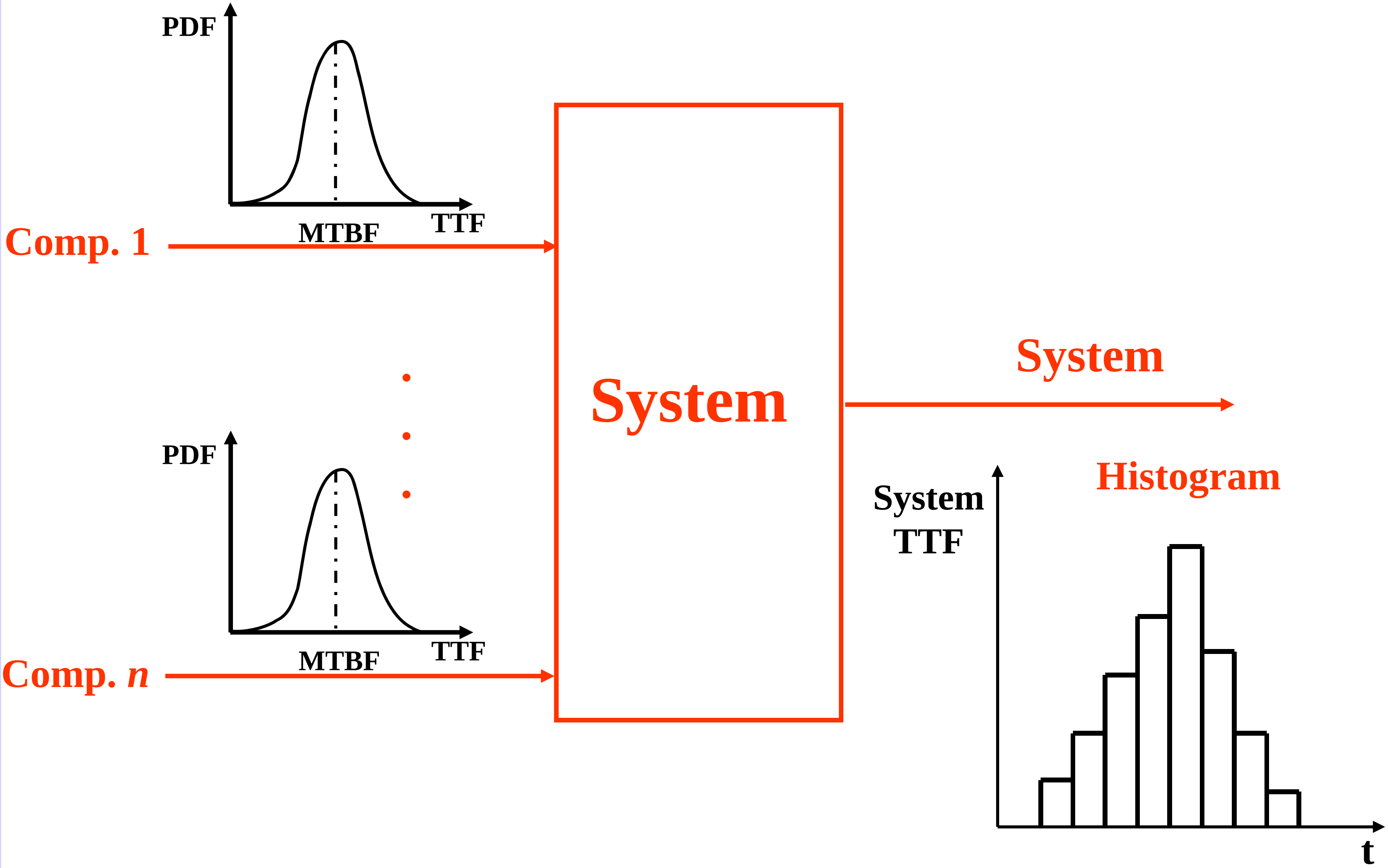
We get:

$$p = \bar{\mu}\left(\frac{\bar{\mu}(1-\bar{\mu})}{\bar{\sigma}^2} - 1\right),$$

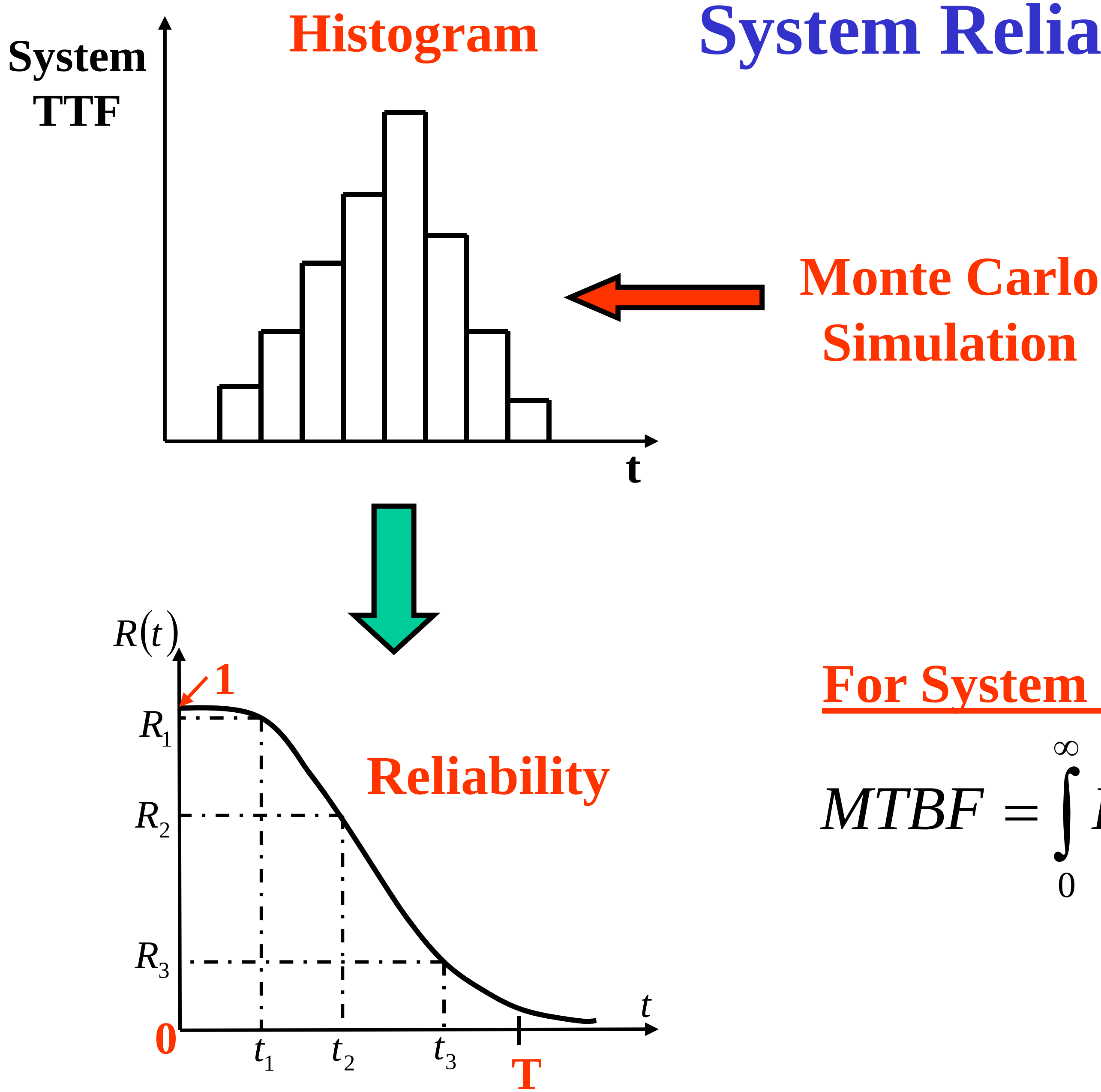
$$q = (1-\bar{\mu})\left(\frac{\bar{\mu}(1-\bar{\mu})}{\bar{\sigma}^2} - 1\right)$$

System Reliability and Reliability Allocation

System Reliability



System Reliability

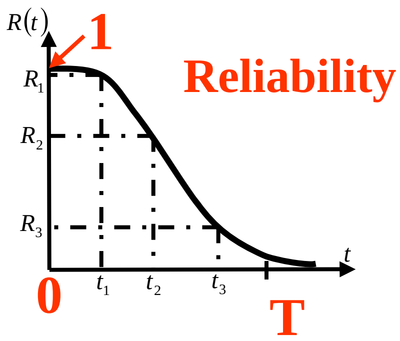


For System :

$$MTBF = \int_0^\infty R(t)dt$$

UNCLASSIFIED: Dist A. Approved for public release

Reliability Allocation



Specify system (vehicle) reliability

Optimization

Determine required reliability of EACH component

This optimization problem DOES NOT have a unique solution

Reliability Allocation

One way to get a unique solution is to trade-off reliability and associated cost

$$\min_{\underline{R}_{comp}} \quad Cost$$

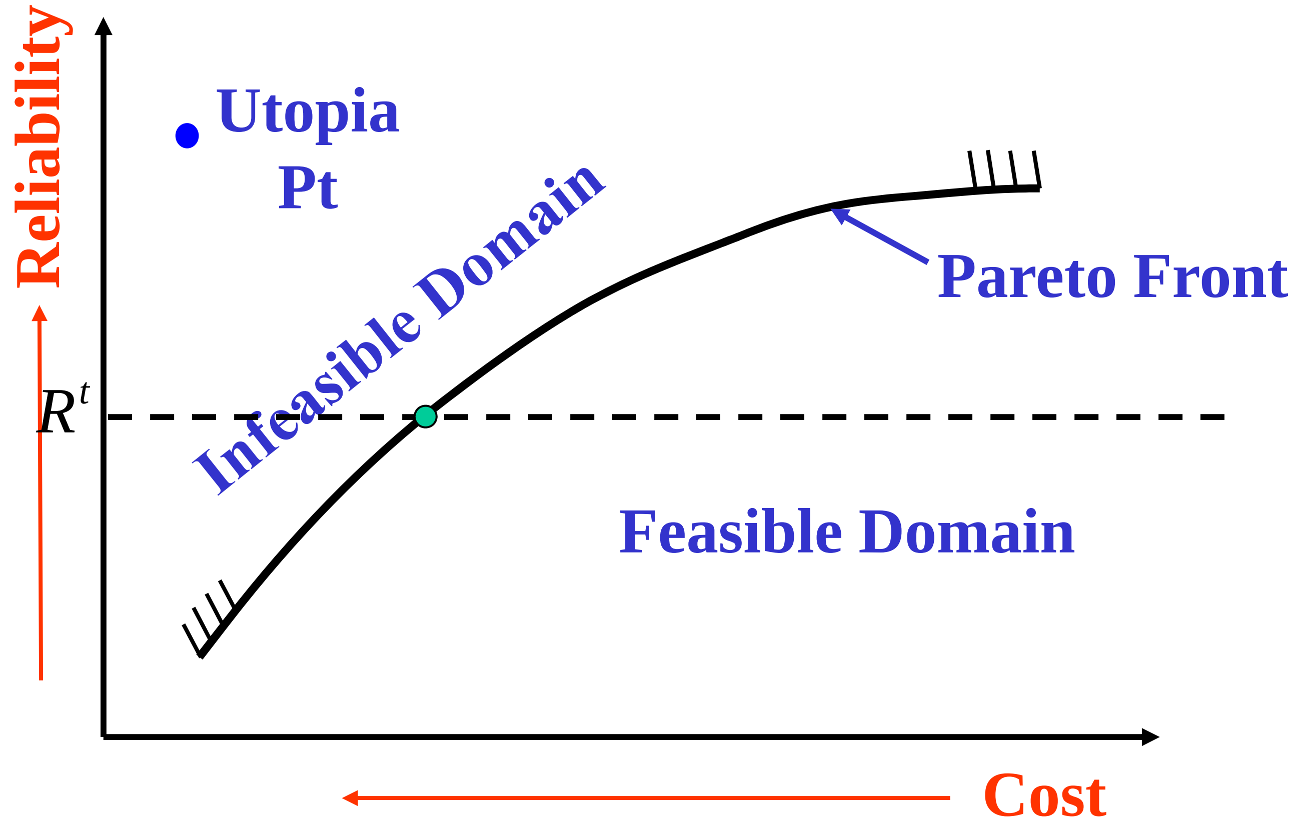
Target system reliability

s. t. $$System \quad Reliability = R^t$$

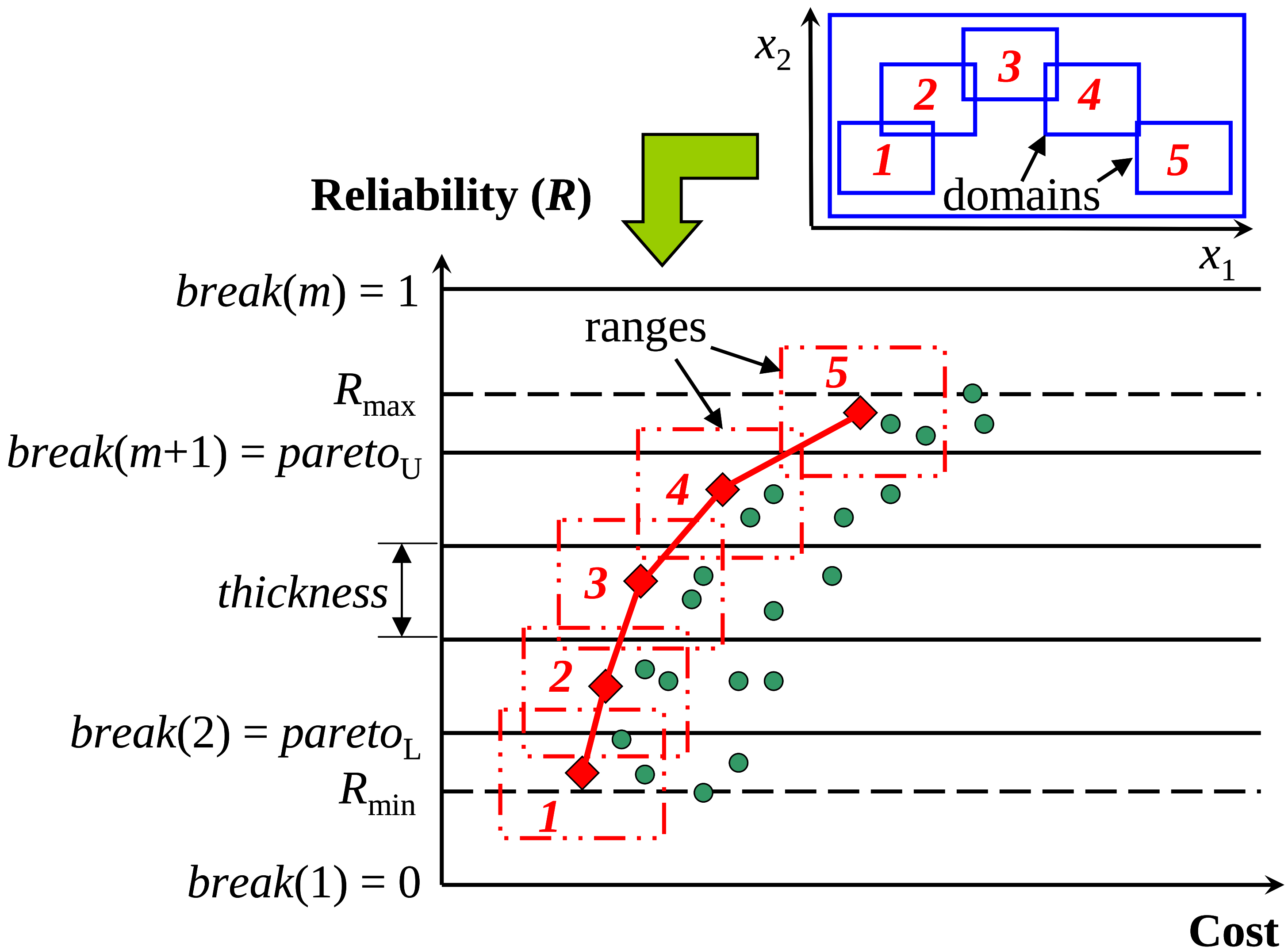
By varying R^t **, we get the so called "Pareto Frontier."**

Reliability vs Risk of Failure (Cost)

We want to maximize Reliability and simultaneously minimize Risk of failure (cost)



Reliability – Cost Pareto Front Calculation

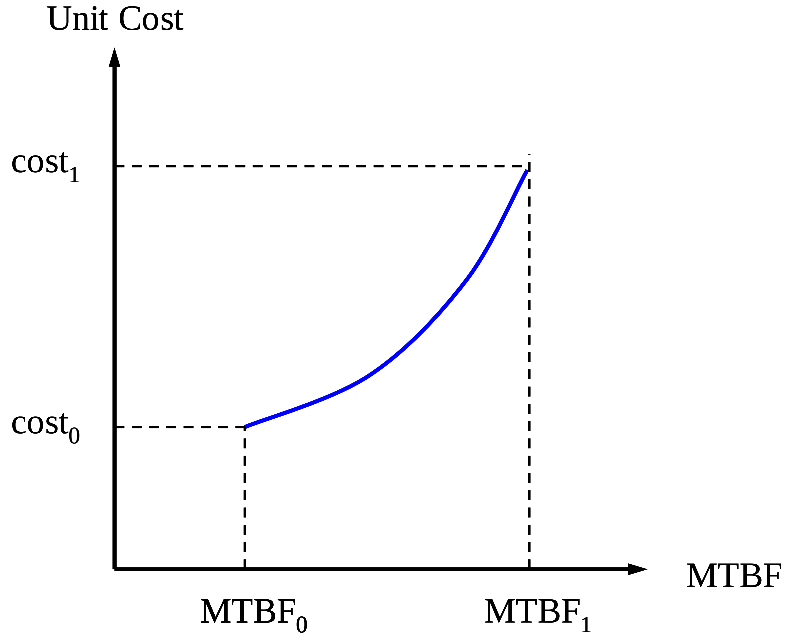


Reliability-Cost Relation

$$\text{cost} = \text{cost}_0 \, e^{k(\text{MTBF}/\text{MTBF}_0 - 1)}$$ **: For each component**

$$\text{Cost} = \sum_{i_C=1}^{N_C} \left[\text{cost}_0 \, e^{k(\text{MTBF}/\text{MTBF}_0 - 1)} (1 + \text{failure counts}) \right]_{i_C}$$

For system with Nc components

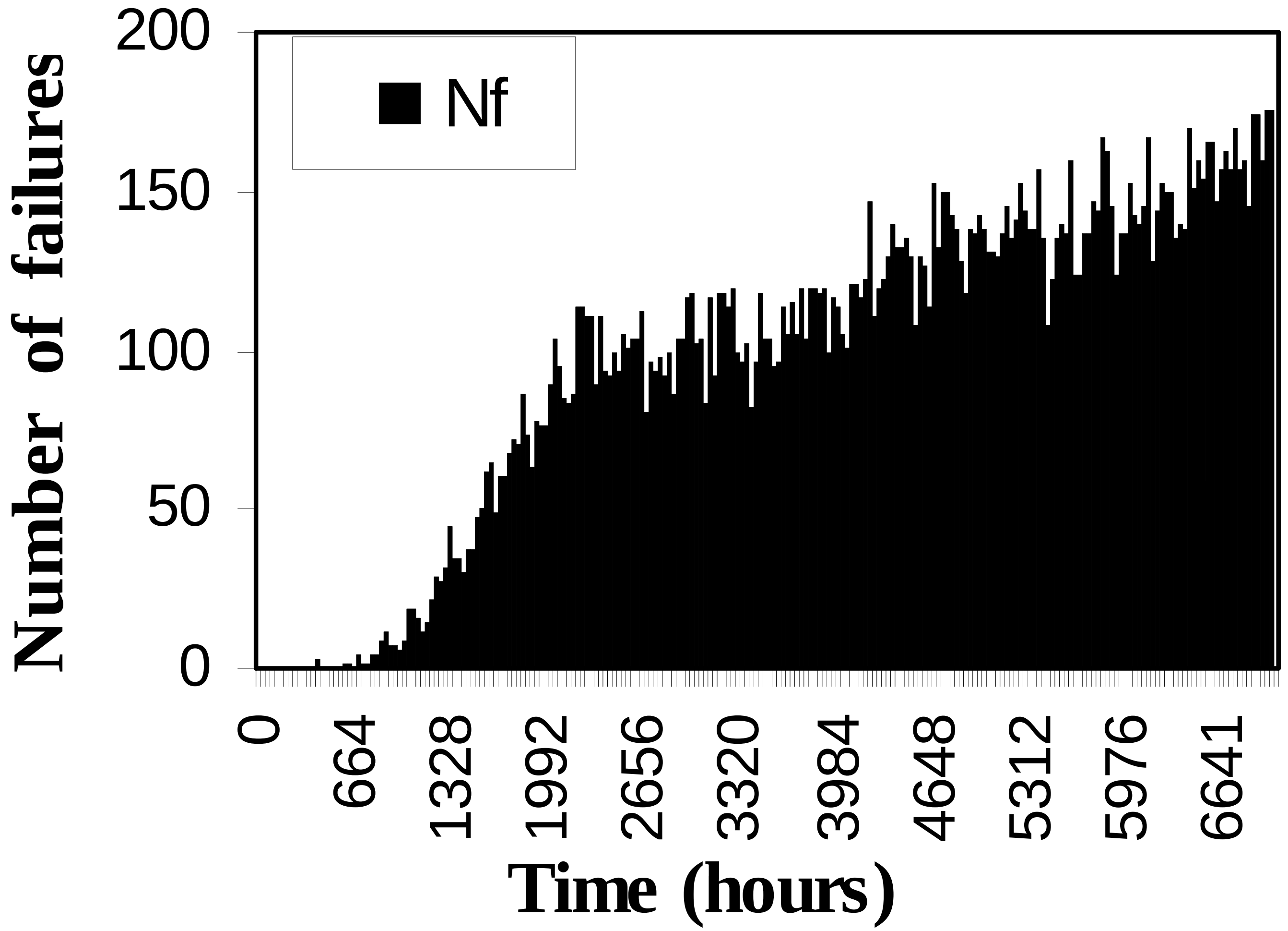


Example : Fifteen-Component System in Series

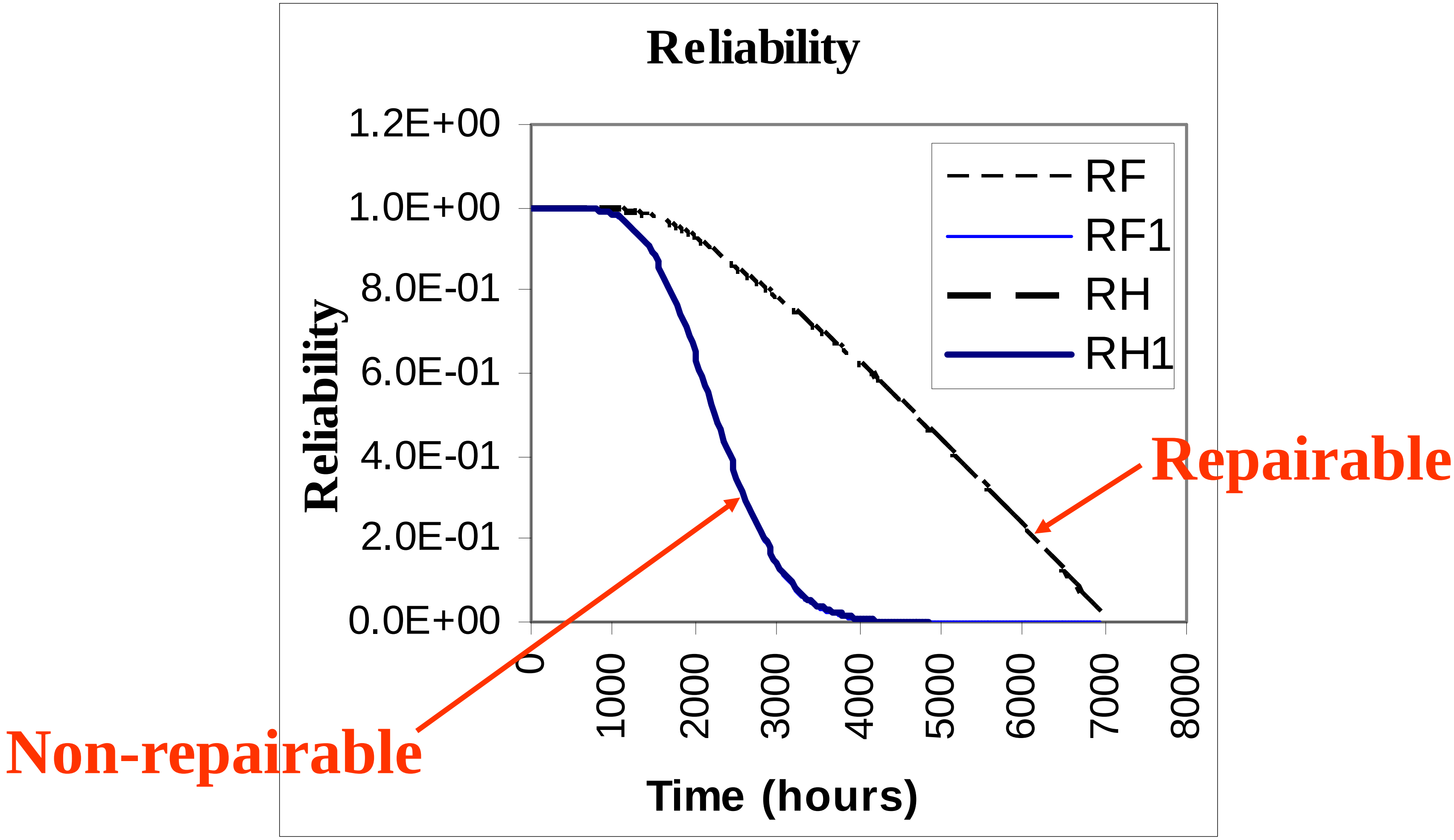
Input Information

Component Number Comp No.	Baseline MTBF in hours ($MTBF_0$)	Coefficient of Variation	B_{factor}	Baseline cost ($Cost_0$)	k
1	4076	0.3	3	$27,500.00	1
2	15000	0.3	3	$7,000.00	1
3	26510	0.3	3	$3,000.00	1
4	40000	0.3	3	$5,000.00	1
5	18000	0.3	3	$5,000.00	1
6	8000	0.3	3	$500.00	1
7	31809	0.3	3	$22,500.00	1
8	9520	0.3	3	$30,000.00	1
9	9713	0.3	3	$12,500.00	1
10	2330	0.3	3	$20,000.00	1
11	40000	0.3	3	$27,500.00	1
12	8614	0.3	3	$1,000.00	1
13	45000	0.3	3	$30,000.00	1
14	20000	0.3	3	$3,000.00	1
15	25000	0.3	3	$15,000.00	1

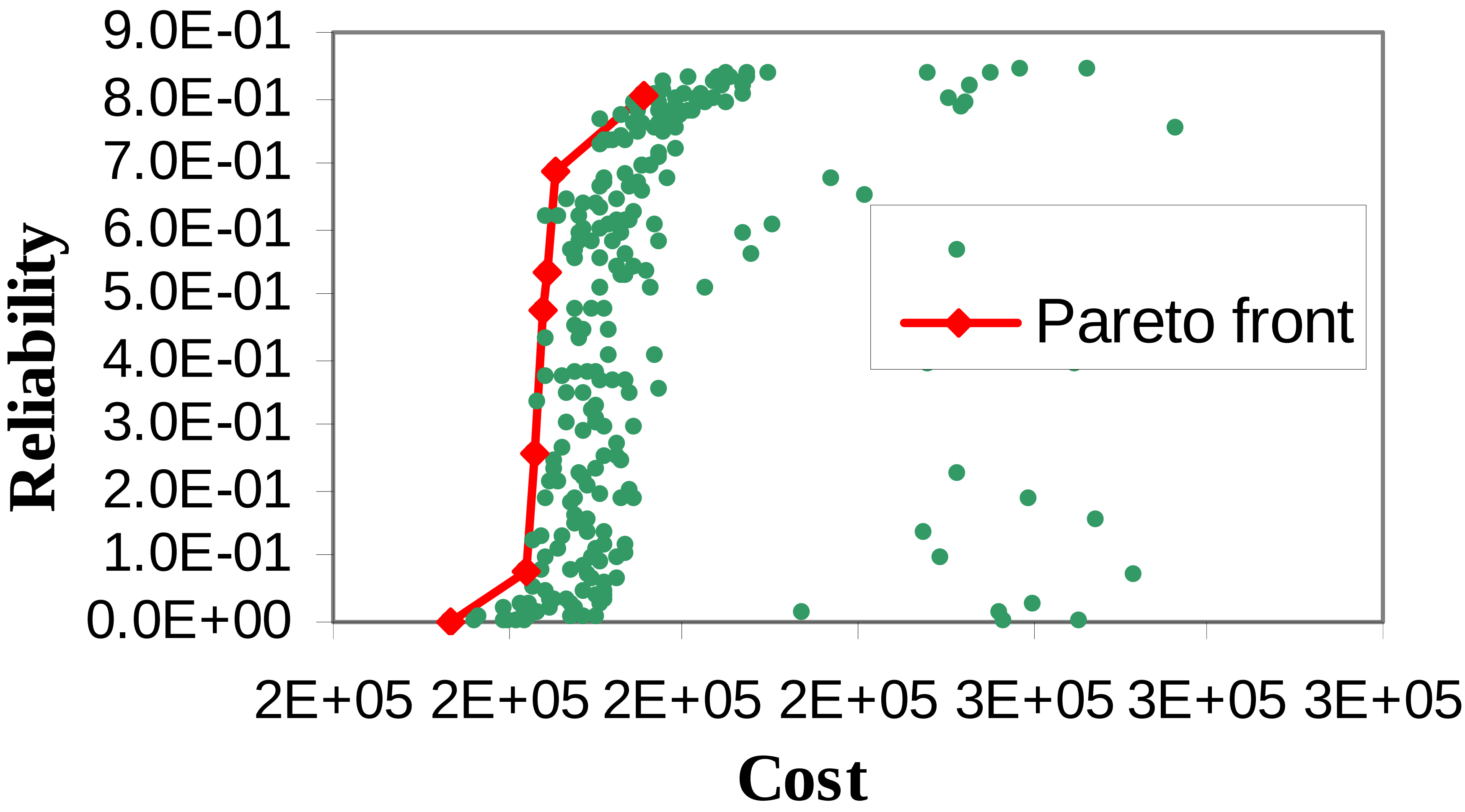
Histogram of System Failures



Reliability Comparison between Repairable and Non-repairable System



System Reliability-Cost Pareto Front



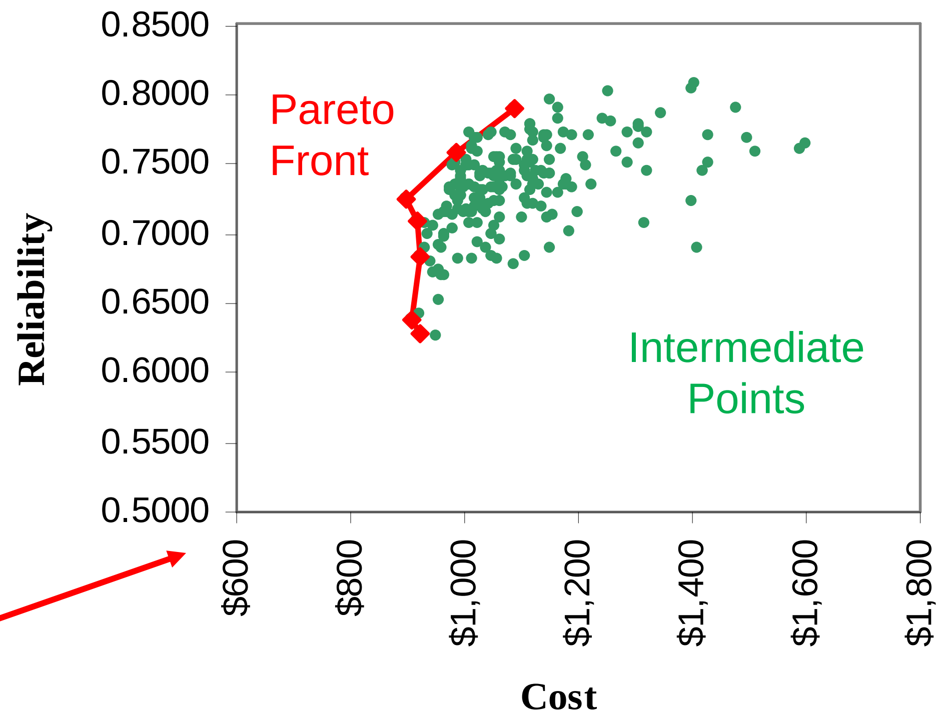
Summary: Methodology

- **A methodology was presented to :**
  - **Calculate system reliability using limited data**
  - **Perform reliability allocation (determine reliabilities of components) using optimal trade-off between reliability and cost**
- **The methodology was demonstrated with a fifteen-component vehicle system**

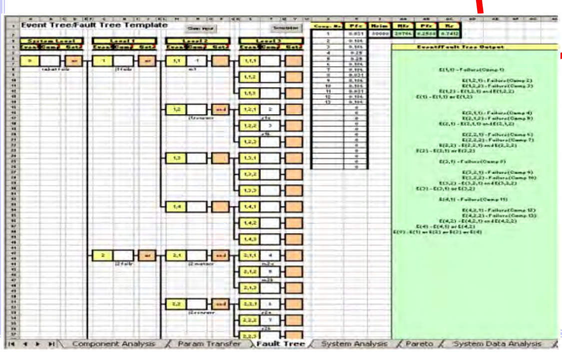
Fleet Maintenance Simulation (FMS) Tool

Simulation and Optimization - FMS Tool

- Developed jointly by TARDEC (CASSI Analytics) and Oakland University
- Predicts vehicle maintenance over lifecycle based on component input data
- Enables reliability-cost trade/sensitivity/optimization studies for vehicle fleets



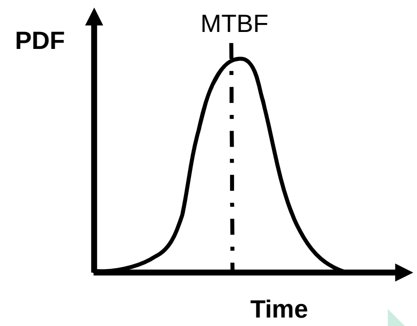
FMS Tool used to perform reliability-cost trade study for adding redundant motors and sensors to an unmanned ground vehicle (UGV) manipulator arm



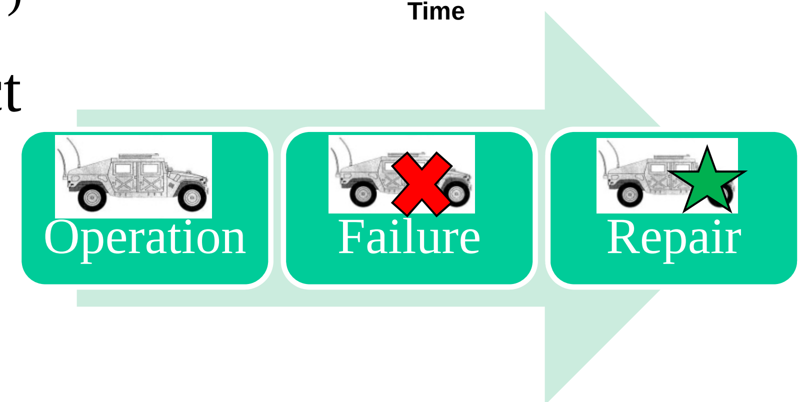
Fault tree in FMS Tool

Analysis Procedure

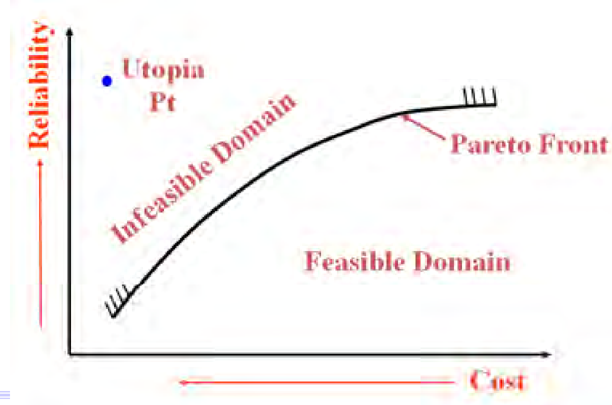
1. Estimate component probability of failure vs time or mileage
   – Focus on cost and repair drivers
   – Minimum data: mean time between failure (MTBF)



2. Run Monte Carlo simulations to predict fleet reliability, availability, cost
   – Vehicle lifetime: user-specified
   – Number of simulated vehicles: user-specified

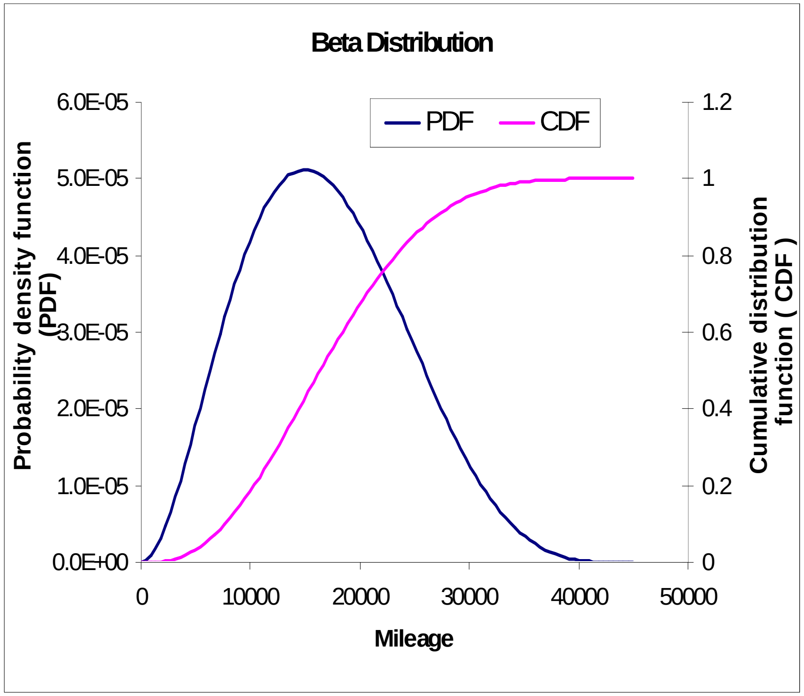


3. Perform trade/sensitivity/optimization studies
   – Tradeoffs among configurations, component changes, maintenance schedules, etc.
   – Sensitivity to data uncertainty, price changes, etc.
   – Optimization of components, schedules, etc.



Estimation of Component Reliability

- Beta distribution family is used to model probability of component failure versus time or mileage
- When maintenance records are available:
  - FMS Tool processes raw data
- For **limited, censored data** FMS Tool has two options to estimate the distribution
  - Censored Maximum Likelihood Estimation (MLE)
  - Bayesian updating approach ("enhances" data with expert opinion)



Example: Unmanned Ground Vehicle (UGV)

- Focus on robotic arm design
- For original design, each joint and the end effector has:
  - 1 motor
  - 1 optical encoder (sensor)
- Perform trade study for adding secondary sensors, motors
- Use reliability @ 1000 hours of operation as input data
  - **Motor: R(1000) = 0.969**
  - **Sensor: R(1000) = 0.814**

Reliability of UGV Arm – Original Design

$$R_s = (0.969 \times 0.814)^4 = 0.387$$

Fault Tree for Original Design

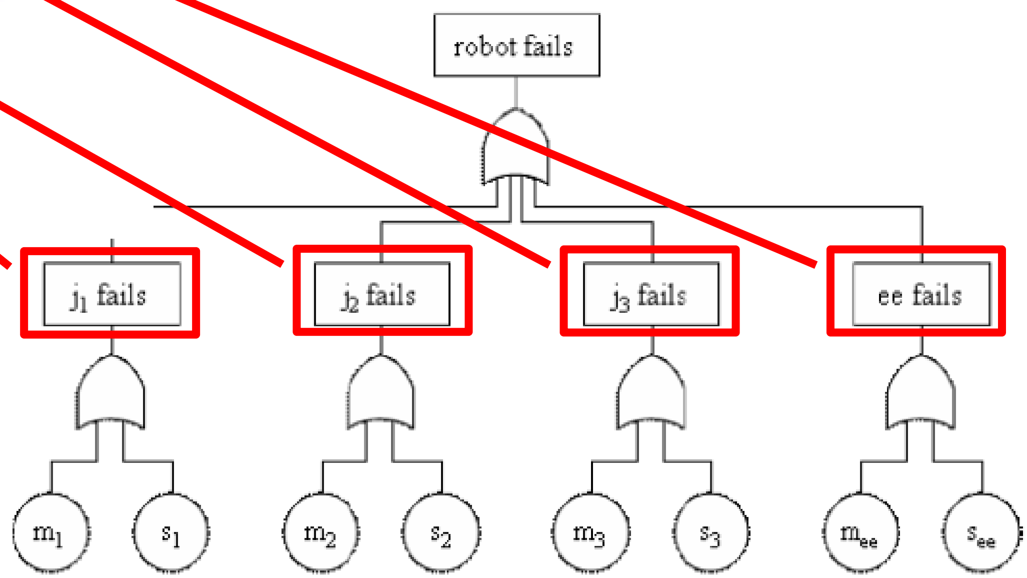


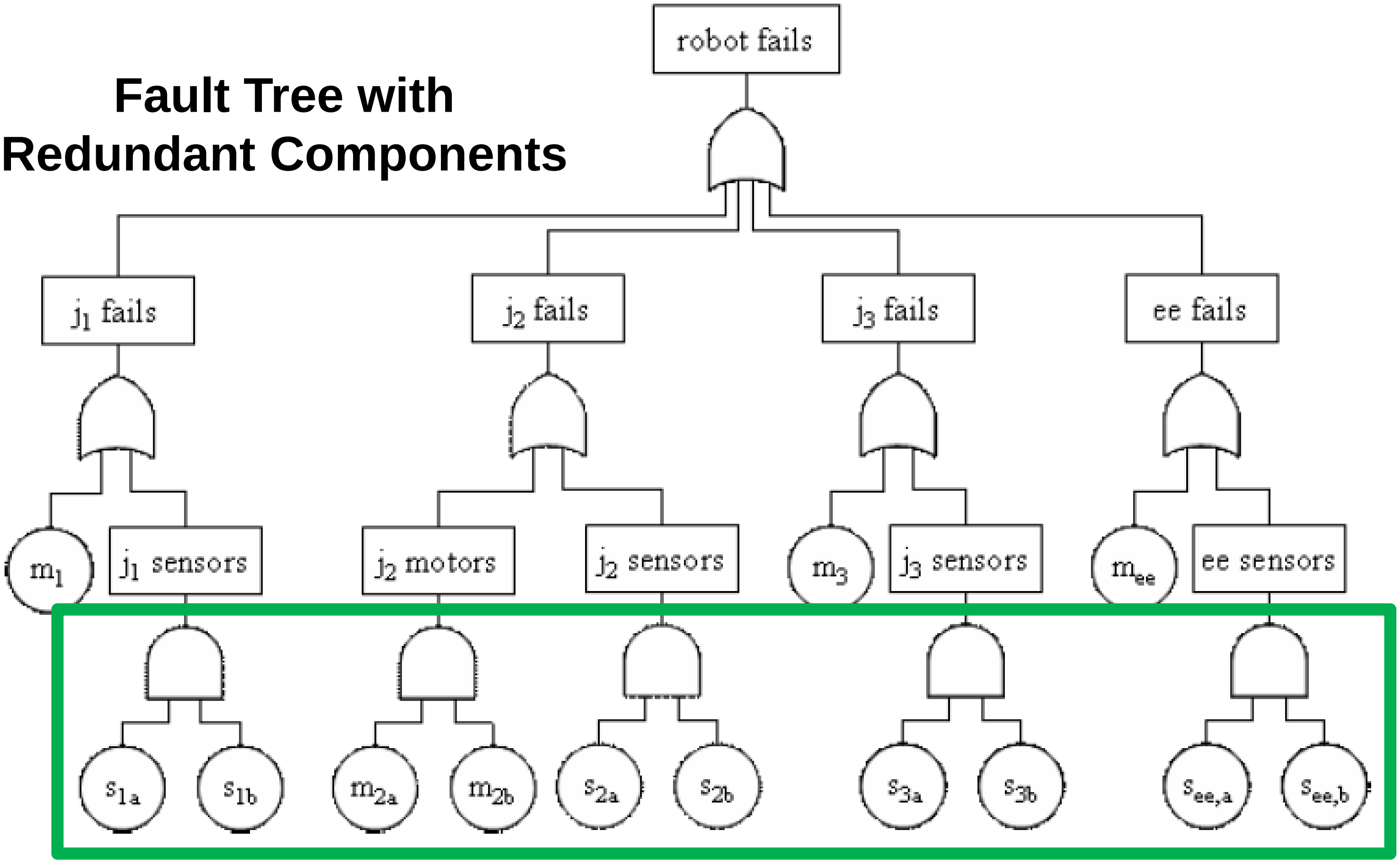
Figure 4. Fault tree for four-joint UGV manipulator with 3DOF and 1DOF servo gripper

j	joint
ee	end effector
m	motor
s	sensor

Reliability for One Design Configuration with Redundant Components

$$R_s = \underbrace{\left\{0.969 \times \left[1-(1-0.814)^2\right]\right\}^3}_{\text{for joints 1, 3, and 4}} \underbrace{\left\{\left[1-(1-0.75)^2\right] \times \left[1-(1-0.814)^2\right]\right\}}_{\text{for joint 2}} = 0.741$$

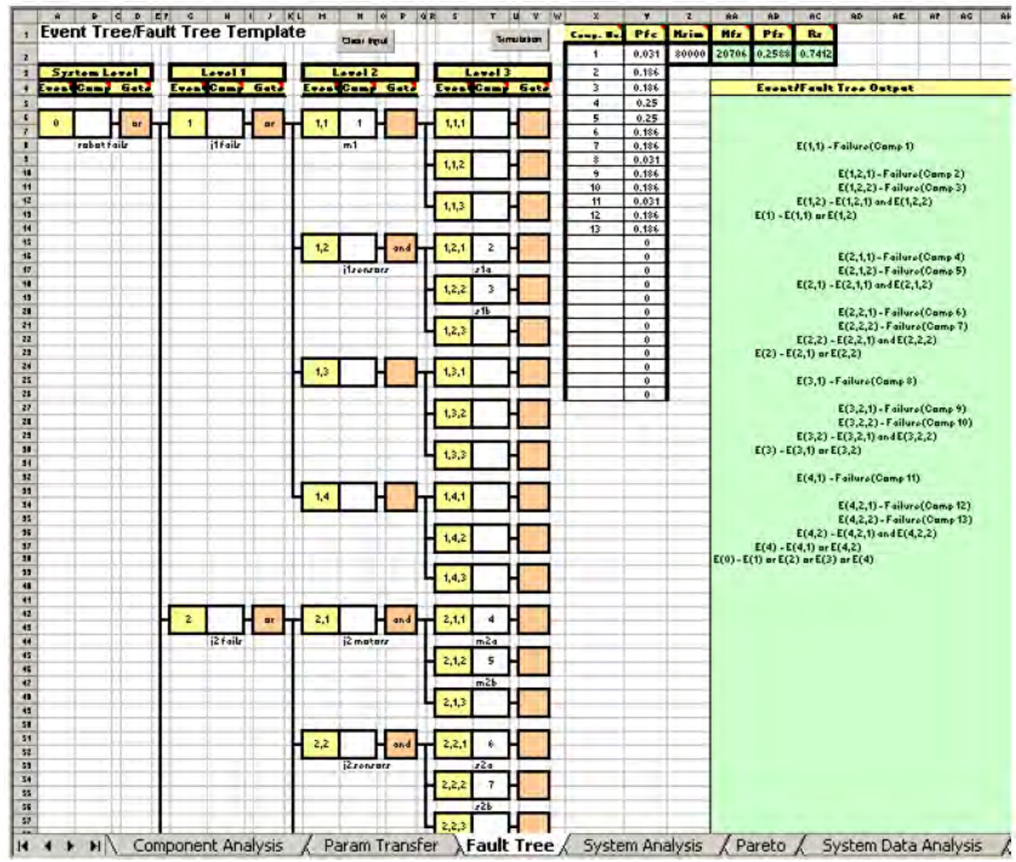
Fault Tree with Redundant Components



Reliability vs. Cost Trade Study

- Redundant components provide higher system reliability, but...
  - At what cost?
  - Is it worth it?

- Use FMS Tool to
  - Perform trade study
  - Find Pareto frontier



Fault Tree Model in FMS Tool

FMS Tool Results: Original Design

Simulation results yield system reliability R=0.75 @ t=1000 hours

Close to theoretical value of 0.741

Total failure Cnts	$R_{sys\ sim}$	Total Cost
0.262249998	0.75	$995.27
failure Cnts	**Unit Cost**	**Sub Total Cost**
0.0272500	$150.00	$154.09
0.0142500	$50.00	$50.71
0.0157500	$50.00	$50.79
0.0220000	$61.62	$62.98
0.0287500	$61.62	$63.39
0.0172500	$50.00	$50.86
0.0162500	$50.00	$50.81
0.0265000	$150.00	$153.98
0.0147500	$50.00	$50.74
0.0180000	$50.00	$50.90
0.0295000	$150.00	$154.43
0.0165000	$50.00	$50.83
0.0155000	$50.00	$50.78

$995

System reliability and cost @ 1000 hours of operation

Component Alternatives

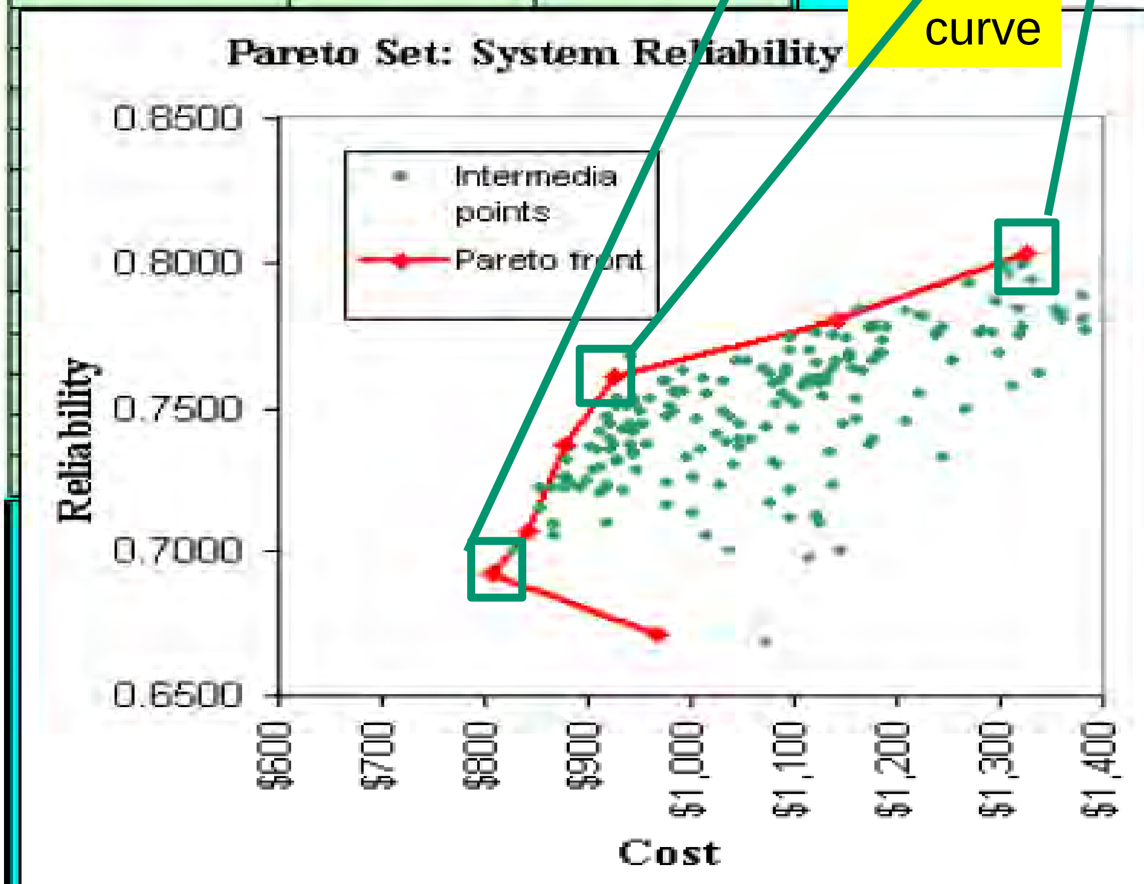
Component Input Data					
Comp. No	$MTBF_0$	Cov	B_{factor}	Unit $Cost_0$	*k*
1	31519	0.98	26.09	$150.00	1
-2	4845	0.77	2.8228	$50.00	1
-3	4845	0.77	2.8228	$50.00	1
4	3476.616	0.98	26.09	$61.62	1
5	3476.616	0.98	26.09	$61.62	1
-6	4845	0.77	2.8228	$50.00	1
-7	4845	0.77	2.8228	$50.00	1
8	31519	0.98	26.09	$150.00	1
-9	4845	0.77	2.8228	$50.00	1
-10	4845	0.77	2.8228	$50.00	1
11	31519	0.98	26.09	$150.00	1
-12	4845	0.77	2.8228	$50.00	1
-13	4845	0.77	2.8228	$50.00	1

Component Input Data

Negative numbers: components that do not have alternatives

FMS Tool Results: Trade Study

Mileage (t)	1000.00	Pareto
N_{pareto}	7	Front
Point ID	*R*	*Cost*
142	0.6713	$968.76
164	0.6925	$807.15
163	0.7077	$842.14
169	0.7376	$877.23
63	0.7607	$925.87
101	0.7806	$1,141.00
195	0.8037	$1,324.79



Reliability-cost Pareto set @ 1000 hours of operation

Recent and Ongoing Work

- **Adding system and fleet attributes**
  - Weight, fuel efficiency/cost
  - Availability
- **Enhancing underlying models**
  - Different types of failure modes, more probability distributions
  - Scheduled maintenance, preventive maintenance
- **Implementing state-of-the-art multi-objective optimizer**
  - Non-dominated sorting genetic algorithm II (NGSA-II)
  - Multiple objectives beyond cost and reliability
- **Converting software framework from Excel to MATLAB**
  - Improve computational performance
  - Leverage MATLAB toolkits
  - Foster collaborative development (TARDEC, OU, SMART Students)

Summary: FMS Tool

- Fleet Maintenance Simulation (FMS) Tool has been developed to perform trade/sensitivity/optimization studies
- FMS Tool applied to example UGV trade study for validation and demonstration purposes
- Software is under active development by TARDEC and OU to enhance capabilities and improve efficiency

Q & A